



University of
Zurich^{UZH}

Zurich Open Repository and
Archive

University of Zurich
University Library
Strickhofstrasse 39
CH-8057 Zurich
www.zora.uzh.ch

Year: 2013

Measurement of CP violation in the phase space of $B^\pm \rightarrow K^\pm + -$ and $B^\pm \rightarrow K^\pm K + K^-$ decays

LHCb Collaboration ; et al ; Bernet, R ; Müller, K ; Steinkamp, O ; Straumann, U ; Vollhardt, A

Abstract: The charmless decays $B^\pm \rightarrow K^\pm + -$ and $B^\pm \rightarrow K^\pm K + K^-$ are reconstructed using data, corresponding to an integrated luminosity of 1.0 fb^{-1} , collected by LHCb in 2011. The inclusive charge asymmetries of these modes are measured as $\text{ACP}(B^\pm \rightarrow K^\pm + -) = 0.032 \pm 0.008 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.007 \text{ (J/K}^\pm\text{)}$ and $\text{ACP}(B^\pm \rightarrow K^\pm K + K^-) = -0.043 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)} \pm 0.007 \text{ (J/K}^\pm\text{)}$, where the third uncertainty is due to the CP asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ reference mode. The significance of $\text{ACP}(B^\pm \rightarrow K^\pm K + K^-)$ exceeds three standard deviations and is the first evidence of an inclusive CP asymmetry in charmless three-body B decays. In addition to the inclusive CP asymmetries, larger asymmetries are observed in localized regions of phase space.

DOI: <https://doi.org/10.1103/PhysRevLett.111.101801>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-91692>

Journal Article

Published Version

Originally published at:

LHCb Collaboration; et al; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A (2013). Measurement of CP violation in the phase space of $B^\pm \rightarrow K^\pm + -$ and $B^\pm \rightarrow K^\pm K + K^-$ decays. Physical Review Letters, 111(10):101801.

DOI: <https://doi.org/10.1103/PhysRevLett.111.101801>



Measurement of CP Violation in the Phase Space of $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ Decays

R. Aaij *et al.**

(LHCb Collaboration)

(Received 5 June 2013; published 3 September 2013)

The charmless decays $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ are reconstructed using data, corresponding to an integrated luminosity of 1.0 fb^{-1} , collected by LHCb in 2011. The inclusive charge asymmetries of these modes are measured as $A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-) = 0.032 \pm 0.008(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K^\pm)$ and $A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-) = -0.043 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}) \pm 0.007(J/\psi K^\pm)$, where the third uncertainty is due to the CP asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ reference mode. The significance of $A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-)$ exceeds three standard deviations and is the first evidence of an inclusive CP asymmetry in charmless three-body B decays. In addition to the inclusive CP asymmetries, larger asymmetries are observed in localized regions of phase space.

DOI: 10.1103/PhysRevLett.111.101801

PACS numbers: 13.25.Hw, 11.30.Er

Violation of the combined symmetry of charge conjugation and parity (CP violation) is described in the standard model by the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1,2]. CP violation is experimentally well established in the K^0 [3], B^0 [4,5], and B^\pm [6] systems. One category of CP violation, known as direct CP violation, requires two interfering amplitudes with different weak and strong phases to be involved in the decay process [7]. Large CP violation effects have been observed in charmless two-body B -meson decays such as $B^0 \rightarrow K^\pm \pi^\mp$ [8,9] and $B^0 s \rightarrow K^\mp \pi^\pm$ [10]. However, the source of the strong phase difference in these processes is not well understood, which limits the potential to use these measurements to search for physics beyond the standard model. One possible source of the required strong phase is from final-state hadron rescattering, which can occur between two or more decay channels with the same flavor quantum numbers, such as $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ [11–14]. This effect, referred to as “compound CP violation” [15] is constrained by CPT conservation so that the sum of the partial decay widths, for all channels with the same final-state quantum numbers related by the S matrix, must be equal for charge-conjugated decays.

Decays of B mesons to three-body hadronic charmless final states provide an interesting environment to search for CP violation through the study of its signatures in the Dalitz plot [16]. Theoretical predictions are mostly based on quasi-two-body decays to intermediate states, e.g., $\rho^0 K^\pm$ and $K^{*0}(892)\pi^\pm$ for $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ decays and ϕK^\pm for $B^\pm \rightarrow K^\pm K^+ K^-$ decays (see, e.g., Ref. [17]). These intermediate states are accessible through amplitude

analyses of data, such as those performed by the Belle and BABAR Collaborations, who reported evidence of CP violation in the intermediate channel $\rho^0 K^\pm$ [18,19] in $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ decays and more recently in the channel ϕK^\pm [20] in $B^\pm \rightarrow K^\pm K^+ K^-$ decays. However, the inclusive CP asymmetry of $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ decays was found to be consistent with zero.

In this Letter, we report measurements of the inclusive CP -violating asymmetries in $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ decays with unprecedented precision. (The inclusion of charge-conjugate decay modes is implied except in the asymmetry definitions.) We also study their asymmetry distributions across the phase space. The CP asymmetry in B^\pm decays to a final state f^\pm is defined as

$$A_{CP}(B^\pm \rightarrow f^\pm) = \Phi[\Gamma(B^- \rightarrow f^-), \Gamma(B^+ \rightarrow f^+)], \quad (1)$$

where $\Phi[X, Y] \equiv (X - Y)/(X + Y)$ is the asymmetry operator, Γ is the decay width, and the final states are $f^\pm = K^\pm \pi^+ \pi^-$ or $f^\pm = K^\pm K^+ K^-$.

The LHCb detector [21] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The analysis is based on pp collision data, corresponding to an integrated luminosity of 1.0 fb^{-1} , collected in 2011 at a center-of-mass energy of 7 TeV.

Events are selected by a trigger [22] that consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Candidate events are first required to pass the hardware trigger, which selects particles with large transverse energy. The software trigger requires a two-, three-, or four-track secondary vertex with a high sum of the transverse momenta p_T of the tracks and a significant displacement from the primary pp interaction vertices (PVs). At least one track should have $p_T > 1.7 \text{ GeV}/c$ and χ^2_{IP} with respect to any primary vertex greater than 16, where χ^2_{IP} is defined as the difference between the χ^2 of a given PV reconstructed with and

*Full author list given at the end of the article.

without the considered track, IP is the impact parameter. A multivariate algorithm is used for the identification of secondary vertices consistent with the decay of a b hadron.

A set of off-line selection criteria is applied to reconstruct B mesons and suppress the combinatorial backgrounds. The B^\pm decay products are required to satisfy a set of selection criteria on their momenta, transverse momenta, the χ^2_{IP} of the final-state tracks, and the distance of closest approach between any two tracks. The B candidates are required to have $p_T > 1.7$ GeV/ c , $\chi^2_{\text{IP}} < 10$ (defined by projecting the B candidate trajectory backwards from its decay vertex) and displacement from any PV greater than 3 mm. Additional requirements are applied to variables related to the B -meson production and decay, such as quality of the track fits for the decay products, and the angle between the B candidate momentum and the direction of flight from the primary vertex to the decay vertex. Final-state kaons and pions are further selected using particle identification information, provided by two ring-imaging Cherenkov detectors [23]. The selection is common to both decay channels, except the particle identification selection, which is specific to each final state. Charm contributions are removed by excluding the regions of ± 30 MeV/ c^2 around the D^0 mass in the two-body invariant masses $m_{\pi\pi}$, $m_{K\pi}$, and m_{KK} . The contribution of the $B^\pm \rightarrow J/\psi K^\pm$ decay is also excluded from the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ sample by removing the mass region $3.05 < m_{\pi\pi} < 3.15$ GeV/ c^2 .

The simulated events used in this analysis are generated using PYTHIA 6.4 [24] with a specific LHCb configuration [25]. Decays of hadronic particles are produced by EVTGEN [26], in which final-state radiation is generated using PHOTOS [27]. The interaction of the generated particles with the detector and its response are implemented using the GEANT 4 toolkit [28], as described in Ref. [29].

Unbinned extended maximum likelihood fits to the mass spectra of the selected B^\pm candidates are performed. The $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ signal components are parametrized by so-called Cruijff functions [30] to

account for the asymmetric effect of final-state radiation on the signal shape. The combinatorial background is described by an exponential function, and the background due to partially reconstructed four-body B decays is parametrized by an ARGUS function [31] convolved with a Gaussian resolution function. Peaking backgrounds occur due to decay modes with one misidentified particle and consist of the channels $B^\pm \rightarrow K^+ K^- \pi^\pm$, $B^\pm \rightarrow \pi^+ \pi^- \pi^\pm$, and $B^\pm \rightarrow \eta'(\rho^0 \gamma) K^\pm$ for the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ mode, and $B^\pm \rightarrow K^+ K^- \pi^\pm$ for the $B^\pm \rightarrow K^\pm K^+ K^-$ mode. The shapes of the peaking backgrounds are obtained from simulation. The peaking background yields are obtained from simulation to be $N_{\eta'/K} = 2140 \pm 154$ (most of which lie at masses lower than the signal), $N_{\pi\pi\pi} = 528 \pm 58$, and $N_{KK\pi} = 219 \pm 25$ for $B^\pm \rightarrow K^\pm \pi^+ \pi^-$, and $N_{KK\pi} = 192 \pm 20$ for $B^\pm \rightarrow K^\pm K^+ K^-$ decays. The invariant mass spectra of the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ candidates are shown in Fig. 1.

The mass fits of the two samples are used to obtain the signal yields $N(K\pi\pi) = 35901 \pm 327$ and $N(KKK) = 22119 \pm 164$, and the raw asymmetries, $A_{\text{raw}}(K\pi\pi) = 0.020 \pm 0.007$ and $A_{\text{raw}}(KKK) = -0.060 \pm 0.007$, where the uncertainties are statistical. In order to determine the CP asymmetries, the measured raw asymmetries are corrected for effects induced by the detector acceptance and interactions of final-state particles with matter, as well as for a possible B -meson production asymmetry. The decay products are regarded as a pair of charge-conjugate hadrons $h^+ h^- = \pi^+ \pi^-$, $K^+ K^-$, and a kaon with the same charge as the B^\pm meson. The CP asymmetry is expressed in terms of the raw asymmetry and a correction A_Δ ,

$$A_{CP} = A_{\text{raw}} - A_\Delta, \quad A_\Delta = A_D(K^\pm) + A_P(B^\pm). \quad (2)$$

Here, $A_D(K^\pm)$ is the kaon detection asymmetry, given in terms of the charge-conjugate kaon detection efficiencies $\varepsilon_D(K^\pm)$ by $A_D(K^\pm) = \Phi[\varepsilon_D(K^-), \varepsilon_D(K^+)]$, and $A_P(B^\pm)$ is the production asymmetry, defined from the B^\pm production rates $R(B^\pm)$ as $A_P(B^\pm) = \Phi[R(B^-), R(B^+)]$.

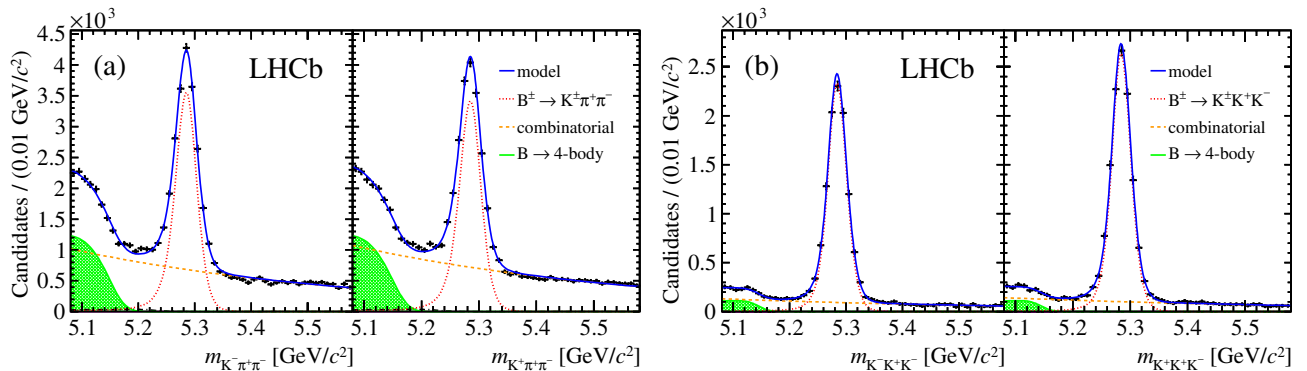


FIG. 1 (color online). Invariant mass spectra of (a) $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ decays and (b) $B^\pm \rightarrow K^\pm K^+ K^-$ decays. The left panel in each figure shows the B^- modes, and the right panel in each shows the B^+ modes. The results of the unbinned maximum likelihood fits are overlaid. The main components of the fit are also shown.

The correction term A_Δ is measured from data using a sample of approximately 6.3×10^4 $B^\pm \rightarrow J/\psi(\mu^+\mu^-)K^\pm$ decays. The $B^\pm \rightarrow J/\psi K^\pm$ sample passes the same trigger, kinematic, and kaon particle identification selections as the signal samples, and it has a similar event topology. The kaons from $B^\pm \rightarrow J/\psi K^\pm$ decay also have similar kinematics in the laboratory frame to those from the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ modes. The correction is obtained from the raw asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ mode as

$$A_\Delta = A_{\text{raw}}(J/\psi K) - A_{CP}(J/\psi K), \quad (3)$$

using the world average of the CP asymmetry $A_{CP}(J/\psi K) = (0.1 \pm 0.7)\%$ [32]. The CP asymmetries of the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ channels are then determined using Eqs. (2) and (3).

Since the detector efficiencies for the signal modes are not flat in the corners of the Dalitz plot and the raw asymmetries are also not uniformly distributed, an acceptance correction is applied to the integrated raw asymmetries. It is determined by the ratio between the B^- and B^+ average efficiencies in simulated events, reweighted to reproduce the population in the Dalitz plot of signal data. Furthermore, the detector acceptance and reconstruction efficiency depend on the trigger selection. The efficiency of the hadronic hardware trigger is found from calibration data to have a small charge asymmetry for final-state kaons. Therefore, the data are divided into two samples with respect to the hadronic hardware trigger decision: events with candidates selected by the hadronic trigger and events selected by other triggers independently of the signal candidate. In order to apply Eq. (3) to $B^\pm \rightarrow K^\pm K^+ K^-$ events selected by the hadronic hardware trigger, the difference in trigger efficiencies caused by the presence of three kaons compared to one kaon is taken into account. The acceptance correction and subtraction of A_Δ are performed separately for each trigger configuration. The trigger-averaged value of the asymmetry correction is $A_\Delta = -0.014 \pm 0.04$, which is consistent with other LHCb analyses [6,33,34]. The integrated CP asymmetries are then the weighted averages of the CP asymmetries for the two trigger samples.

The systematic uncertainties on the asymmetries are related to the mass fit models, possible trigger asymmetry, and phase-space acceptance correction. In order to estimate the uncertainty due to the choice of the signal mass shape, the initial model is replaced with the sum of a Gaussian and a crystal ball function [35]. The uncertainty associated with the combinatorial background model is estimated by repeating the fit with a first-order polynomial. We evaluate three uncertainties related to the peaking backgrounds: one due to the uncertainty on their yields, another due to the difference in mass resolution between simulation and data, and a third due to their possible non-zero asymmetries. The deviations from the nominal results

are accounted for as systematic uncertainties. The systematic uncertainties related to the possible asymmetry induced by the trigger selection are of two kinds: one due to an asymmetric response of the hadronic hardware trigger to kaons and a second due to the choice of sample division by trigger decision. The former is evaluated by reweighting the $B^\pm \rightarrow J/\psi K^\pm$ mode with the charge-separated kaon efficiencies from calibration data. The latter is determined by varying the trigger composition of the samples in order to estimate the systematic differences in trigger admixture between the signal channels and the $B^\pm \rightarrow J/\psi K^\pm$ mode. Two distinct uncertainties are attributed to the phase-space acceptance corrections: one is obtained from the uncertainty on the detection efficiency given by the simulation, and the other, due to the choice of binning, is evaluated by varying the binning of the acceptance map. The systematic uncertainties for the measurements of $A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-)$ and $A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-)$ are summarized in Table I.

The results obtained for the inclusive CP asymmetries of the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ decays are

$$A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007,$$

$$A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007,$$

where the first uncertainty is statistical, the second is the experimental systematic, and the third is due to the CP asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ reference mode [32]. The significances of the inclusive charge asymmetries, calculated by dividing the central values by the sum in quadrature of the statistical and both systematic uncertainties, are 2.8 standard deviations (σ) for $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and 3.7 σ for $B^\pm \rightarrow K^\pm K^+ K^-$ decays.

In addition to the inclusive charge asymmetries, we also study the asymmetry distributions in the two-dimensional phase space of two-body invariant masses. The background-subtracted Dalitz plot distributions of the signal region, defined as the mass region within three Gaussian widths from the signal peak, are divided into bins with equal numbers of events in the combined B^- and B^+ samples. The background under the signal is estimated from the sideband distributions. A raw asymmetry variable $A_{\text{raw}}^N = \Phi[N(B^-), N(B^+)]$ is computed from

TABLE I. Systematic uncertainties on $A_{CP}(K^\pm \pi^+ \pi^-)$ and $A_{CP}(K^\pm K^+ K^-)$. The total systematic uncertainties are the sum in quadrature of the individual contributions.

Systematic uncertainty	$A_{CP}(K\pi\pi)$	$A_{CP}(KKK)$
Signal model	0.0010	0.0002
Combinatorial background	0.0006	<0.0001
Peaking background	0.0007	0.0001
Trigger asymmetry	0.0036	0.0019
Acceptance correction	0.0012	0.0019
Total	0.0040	0.0027

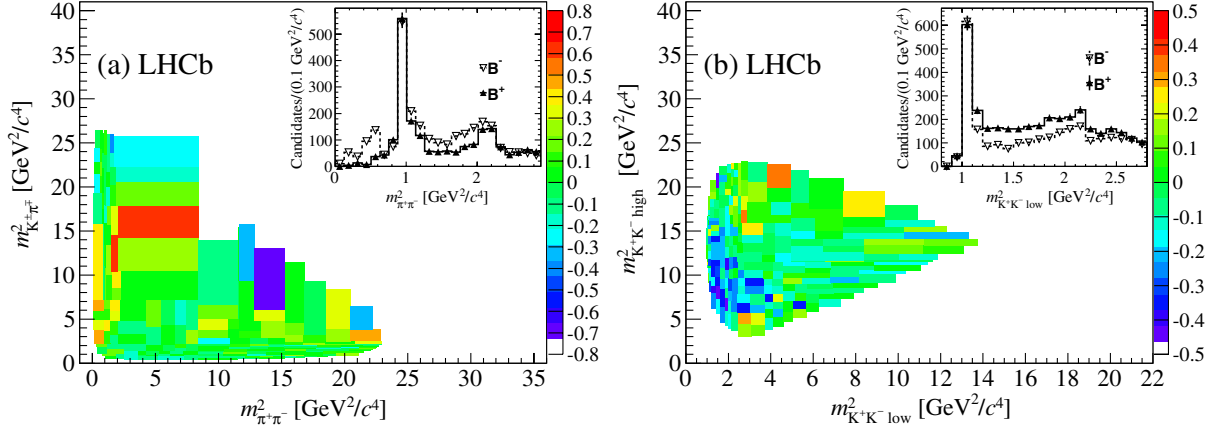


FIG. 2 (color online). Asymmetries of the number of signal events in bins of the Dalitz plot A_{raw}^N for (a) $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and (b) $B^\pm \rightarrow K^\pm K^+ K^-$ decays. The inset figures show the projections of the number of background-subtracted events in bins of (left) the $m_{\pi^+ \pi^-}^2$ variable for $m_{K^\pm \pi^\mp}^2 < 15 \text{ GeV}^2/c^4$ and (right) the $m_{K^+ K^-}^2$ variable for $m_{K^+ K^-}^2 < 15 \text{ GeV}^2/c^4$. The distributions are not corrected for acceptance.

the number $N(B^\pm)$ of negative and positive entries in each bin of the background-subtracted Dalitz plots.

The distributions of the A_{raw}^N variable in the Dalitz plots of $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ are shown in Fig. 2, where the $B^\pm \rightarrow K^\pm K^+ K^-$ Dalitz plot is symmetrized and its two-body invariant mass squared variables are defined as $m_{K^+ K^-}^2 < m_{K^+ K^-}^2$. For $B^\pm \rightarrow K^\pm \pi^+ \pi^-$, we identify a positive asymmetry located in the low $\pi^+ \pi^-$ invariant mass region, around the $\rho(770)^0$ resonance, as seen by Belle [18] and BABAR [19], and above the $f_0(980)$ resonance. This can also be seen in the inset figure of the $\pi^+ \pi^-$ invariant mass projection, where there is an excess of B^- candidates. No significant asymmetry is present in the low-mass region of the $K^\pm \pi^\mp$ invariant mass projection. The A_{raw}^N distribution of the $B^\pm \rightarrow K^\pm K^+ K^-$ mode reveals an asymmetry concentrated at low values of $m_{K^+ K^-}^2$ and $m_{K^+ K^-}^2$ in the Dalitz plot. The distribution of the projection of the number of events onto the $m_{K^+ K^-}^2$ invariant mass (inset in the right plot of Fig. 2)

shows that this asymmetry is not related to the $\phi(1020)$ resonance but is instead located in the region $1.2 < m_{K^+ K^-}^2 < 2.0 \text{ GeV}^2/c^4$.

The CP asymmetry in each of the channels is further studied in the region where the raw asymmetry is observed to be large. The $B^\pm \rightarrow K^\pm K^+ K^-$ region $m_{K^+ K^-}^2 < 15 \text{ GeV}^2/c^4$ and $1.2 < m_{K^+ K^-}^2 < 2.0 \text{ GeV}^2/c^4$ is defined such that the $\phi(1020)$ resonance is excluded. For the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ mode, we measure the CP asymmetry of the region $m_{K^\pm \pi^\mp}^2 < 15 \text{ GeV}^2/c^4$ and $0.08 < m_{\pi^+ \pi^-}^2 < 0.66 \text{ GeV}^2/c^4$, which spans the lowest $\pi^+ \pi^-$ masses, including the $\rho(770)^0$ resonance. Unbinned extended maximum likelihood fits are performed to the mass spectra of the candidates in the two regions, using the same models as the global fits. The spectra are shown in Fig. 3. The resulting signal yields and raw asymmetries for the two regions are $N_{\text{reg}}(K\pi\pi) = 552 \pm 47$ and $A_{\text{raw}}^{\text{reg}}(K\pi\pi) = 0.687 \pm 0.078$ for the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ mode, and $N_{\text{reg}}(KKK) = 2581 \pm 55$ and $A_{\text{raw}}^{\text{reg}}(KKK) = -0.239 \pm 0.020$ for the

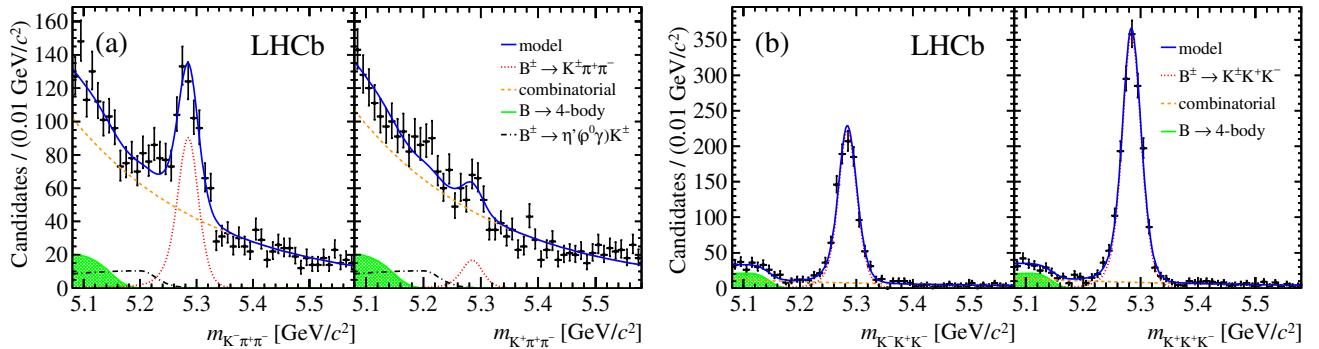


FIG. 3 (color online). Invariant mass spectra of (a) $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ decays in the region $0.08 < m_{\pi^+ \pi^-}^2 < 0.66 \text{ GeV}^2/c^4$ and $m_{K^\pm \pi^\mp}^2 < 15 \text{ GeV}^2/c^4$, and (b) $B^\pm \rightarrow K^\pm K^+ K^-$ decays in the region $1.2 < m_{K^+ K^-}^2 < 2.0 \text{ GeV}^2/c^4$ and $m_{K^+ K^-}^2 < 15 \text{ GeV}^2/c^4$. The left panel in each figure shows the B^- modes, and the right panels show the B^+ modes. The results of the unbinned maximum likelihood fits are overlaid.

$B^\pm \rightarrow K^\pm K^+ K^-$ mode. The CP asymmetries are obtained from the raw asymmetries by applying an acceptance correction and subtracting the detection and production asymmetry correction A_Δ obtained from $B^\pm \rightarrow J/\psi K^\pm$ decays. The validity of the global A_Δ from $B^\pm \rightarrow J/\psi K^\pm$ decays for the results in the regions was tested by comparing the kinematic distributions of their decay products. Systematic uncertainties are estimated due to the signal models, trigger asymmetry, acceptance correction for the region, and the limited validity of Eq. (2) for large asymmetries. The local charge asymmetries for the two regions are measured to be

$$A_{CP}^{\text{reg}}(K\pi\pi) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007,$$

$$A_{CP}^{\text{reg}}(KKK) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007,$$

where the first uncertainty is statistical, the second is the experimental systematic, and the third is due to the CP asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ reference mode.

In conclusion, we have measured the inclusive CP asymmetries of the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ modes with significances of 2.8σ and 3.7σ , respectively. The latter represents the first evidence of an inclusive CP asymmetry in charmless three-body B decays. These charge asymmetries are not uniformly distributed in the phase space. For $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ decays, we observe positive asymmetries at low $\pi^+ \pi^-$ masses, around the $\rho(770)^0$ resonance, as indicated by Belle [18] and BABAR [19], and also above the $f_0(980)$ resonance, where it is not clearly associated to resonances. The asymmetry appears only at low $K^\pm \pi^\mp$ mass around the $\rho(770)^0$ invariant mass. A signature of CP violation is present in the $B^\pm \rightarrow K^\pm K^+ K^-$ Dalitz plot, mostly concentrated in the region of low $m_{K^+ K^-}^2$ and low $m_{K^+ K^-}^2$. A similar pattern of the CP asymmetry was shown in the preliminary results of the $B^\pm \rightarrow K^+ K^- \pi^\pm$ and $B^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ decay modes by LHCb [36], in which the positive asymmetries are at low $\pi^+ \pi^-$ masses and the negative at low $K^+ K^-$ masses, both not clearly associated with intermediate resonant states.

Moreover, the excess of $B^- \rightarrow K^- \pi^+ \pi^-$ decays with respect to $B^+ \rightarrow K^+ \pi^+ \pi^-$ is comparable to the excess of $B^+ \rightarrow K^+ K^+ K^-$ decays with respect to $B^- \rightarrow K^- K^+ K^-$. This apparent correlation, together with the inhomogeneous CP asymmetry distribution in the Dalitz plot, could be related to compound CP violation. Since the $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ modes have the same flavor quantum numbers (as do the pair $B^\pm \rightarrow K^+ K^- \pi^\pm$ and $B^\pm \rightarrow \pi^+ \pi^- \pi^\pm$), CP violation induced by hadron rescattering could play an important role in these charmless three-body B decays. In order to quantify a possible compound CP asymmetry, the introduction of new amplitude analysis techniques, which would take into account the presence of hadron rescattering in three-body B decays, is necessary.

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of

the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ, and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF, and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR, and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal, and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); and NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centers are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (Netherlands), PIC (Spain), and GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

-
- [1] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).
 - [2] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
 - [3] J. Christenson, J. Cronin, V. Fitch, and R. Turlay, *Phys. Rev. Lett.* **13**, 138 (1964).
 - [4] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **87**, 091801 (2001).
 - [5] K. Abe *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **87**, 091802 (2001).
 - [6] R. Aaij *et al.* (LHCb Collaboration), *Phys. Lett. B* **712**, 203 (2012).
 - [7] M. Bander, D. Silverman, and A. Soni, *Phys. Rev. Lett.* **43**, 242 (1979).
 - [8] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **93**, 131801 (2004).
 - [9] Y. Chao *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **93**, 191802 (2004).
 - [10] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **110**, 221601 (2013).
 - [11] R. Marshak, Riazuddin, and C. Ryan, *Theory of Weak Interactions in Particle Physics* (Wiley-Interscience, New York, 1969).
 - [12] L. Wolfenstein, *Phys. Rev. D* **43**, 151 (1991).
 - [13] G.C. Branco, L. Lavoura, and J.P. Silva, *CP Violation* (Oxford University Press, New York, 1999).
 - [14] I.I. Bigi and A. Sanda, *CP Violation* (Cambridge University Press, Cambridge, 1999).
 - [15] H.-Y. Cheng, C.-K. Chua, and A. Soni, *Phys. Rev. D* **71**, 014030 (2005).
 - [16] I. Bediaga, I.I. Bigi, A. Gomes, G. Guerrer, J. Miranda, and A.C. dos Reis, *Phys. Rev. D* **80**, 096006 (2009); I. Bediaga, J. Miranda, A.C. dos Reis, I.I. Bigi, A. Gomes, J.M. Otalora Goicochea, and A. Veiga, *Phys. Rev. D* **86**, 036005 (2012).
 - [17] M. Beneke and M. Neubert, *Nucl. Phys.* **B675**, 333 (2003).

- [18] A. Garmash *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **96**, 251803 (2006).
- [19] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* **78**, 012004 (2008).
- [20] J.-P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **85**, 112010 (2012).
- [21] A. A. Alves, Jr. *et al.* (LHCb Collaboration), *JINST* **3**, S08005 (2008).
- [22] R. Aaij *et al.*, *JINST* **8**, P04022 (2013).
- [23] M. Adinolfi *et al.*, *Eur. Phys. J. C* **73**, 2431 (2013).
- [24] T. Sjöstrand, S. Mrenna, and P. Skands, *J. High Energy Phys.* **05** (2006) 026.
- [25] I. Belyaev *et al.*, in *Proceedings of the Nuclear Science Symposium Conference Record (NSS/MIC)* (IEEE, New York, 2010), p. 1155.
- [26] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [27] P. Golonka and Z. Was, *Eur. Phys. J. C* **45**, 97 (2006).
- [28] J. Allison *et al.* (GEANT4 Collaboration), *IEEE Trans. Nucl. Sci.* **53**, 270 (2006); S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [29] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [30] P. del Amo Sanchez *et al.* (BABAR Collaboration), *Phys. Rev. D* **82**, 051101 (2010).
- [31] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **229**, 304 (1989).
- [32] J. Beringer *et al.* (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012).
- [33] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. D* **85**, 091105 (2012).
- [34] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **108**, 201601 (2012).
- [35] T. Skwarnicki, Ph.D. thesis, Institute of Nuclear Physics, Krakow [Institute of Nuclear Physics Report No. DESY-F31-86-02, 1986 (unpublished)].
- [36] LHCb Collaboration, LHCb Report No. LHCb-CONF-2012-028, 2012.

R. Aaij,⁴⁰ B. Adeva,³⁶ M. Adinolfi,⁴⁵ C. Adrover,⁶ A. Affolder,⁵¹ Z. Ajaltouni,⁵ J. Albrecht,⁹ F. Alessio,³⁷ M. Alexander,⁵⁰ S. Ali,⁴⁰ G. Alkhazov,²⁹ P. Alvarez Cartelle,³⁶ A. A. Alves Jr.,^{24,37} S. Amato,² S. Amerio,²¹ Y. Amhis,⁷ L. Anderlini,^{17,f} J. Anderson,³⁹ R. Andreassen,⁵⁶ J. E. Andrews,⁵⁷ R. B. Appleby,⁵³ O. Aquines Gutierrez,¹⁰ F. Archilli,¹⁸ A. Artamonov,³⁴ M. Artuso,⁵⁸ E. Aslanides,⁶ G. Auriemma,^{24,m} M. Baalouch,⁵ S. Bachmann,¹¹ J. J. Back,⁴⁷ C. Baesso,⁵⁹ V. Balagura,³⁰ W. Baldini,¹⁶ R. J. Barlow,⁵³ C. Barschel,³⁷ S. Barsuk,⁷ W. Barter,⁴⁶ Th. Bauer,⁴⁰ A. Bay,³⁸ J. Beddow,⁵⁰ F. Bedeschi,²² I. Bediaga,¹ S. Belogurov,³⁰ K. Belous,³⁴ I. Belyaev,³⁰ E. Ben-Haim,⁸ G. Bencivenni,¹⁸ S. Benson,⁴⁹ J. Benton,⁴⁵ A. Berezhniov,³¹ R. Bernert,³⁹ M.-O. Bettler,⁴⁶ M. van Beuzekom,⁴⁰ A. Bien,¹¹ S. Bifani,⁴⁴ T. Bird,⁵³ A. Bizzeti,^{17,h} P. M. Bjørnstad,⁵³ T. Blake,³⁷ F. Blanc,³⁸ J. Blouw,¹¹ S. Blusk,⁵⁸ V. Bocci,²⁴ A. Bondar,³³ N. Bondar,²⁹ W. Bonivento,¹⁵ S. Borghi,⁵³ A. Borgia,⁵⁸ T. J. V. Bowcock,⁵¹ E. Bowen,³⁹ C. Bozzi,¹⁶ T. Brambach,⁹ J. van den Brand,⁴¹ J. Bressieux,³⁸ D. Brett,⁵³ M. Britsch,¹⁰ T. Britton,⁵⁸ N. H. Brook,⁴⁵ H. Brown,⁵¹ I. Burducea,²⁸ A. Bursche,³⁹ G. Busetto,^{21,q} J. Buytaert,³⁷ S. Cadeddu,¹⁵ O. Callot,⁷ M. Calvi,^{20,j} M. Calvo Gomez,^{35,n} A. Camboni,³⁵ P. Campana,^{18,37} D. Campora Perez,³⁷ A. Carbone,^{14,c} G. Carboni,^{23,n} R. Cardinale,^{19,i} A. Cardini,¹⁵ H. Carranza-Mejia,⁴⁹ L. Carson,⁵² K. Carvalho Akiba,² G. Casse,⁵¹ L. Castillo Garcia,³⁷ M. Cattaneo,³⁷ Ch. Cauet,⁹ R. Cenci,⁵⁷ M. Charles,⁵⁴ Ph. Charpentier,³⁷ P. Chen,^{3,38} N. Chiapolini,³⁹ M. Chrzasczcz,²⁵ K. Ciba,³⁷ X. Cid Vidal,³⁷ G. Ciezarek,⁵² P. E. L. Clarke,⁴⁹ M. Clemencic,³⁷ H. V. Cliff,⁴⁶ J. Closier,³⁷ C. Coca,²⁸ V. Coco,⁴⁰ J. Cogan,⁶ E. Cogneras,⁵ P. Collins,³⁷ A. Comerma-Montells,³⁵ A. Contu,^{15,37} A. Cook,⁴⁵ M. Coombes,⁴⁵ S. Coquereau,⁸ G. Corti,³⁷ B. Couturier,³⁷ G. A. Cowan,⁴⁹ D. C. Craik,⁴⁷ S. Cunliffe,⁵² R. Currie,⁴⁹ C. D'Ambrosio,³⁷ P. David,⁸ P. N. Y. David,⁴⁰ A. Davis,⁵⁶ I. De Bonis,⁴ K. De Bruyn,⁴⁰ S. De Capua,⁵³ M. De Cian,³⁹ J. M. De Miranda,⁵⁹ L. De Paula,⁶⁰ W. De Silva,⁵⁶ P. De Simone,¹⁸ D. Decamp,⁴ M. Deckenhoff,⁹ L. Del Buono,⁸ N. Deléage,⁴ D. Derkach,⁵⁴ O. Deschamps,⁵ F. Dettori,⁴¹ A. Di Canto,¹¹ F. Di Ruscio,^{23,k} H. Dijkstra,³⁷ M. Dogaru,²⁸ S. Donleavy,⁵¹ F. Dordei,¹¹ A. Dosil Suárez,³⁶ D. Dossett,⁴⁷ A. Dovbnya,⁴² F. Dupertuis,³⁸ R. Dzhelyadin,³⁴ A. Dziurda,²⁵ A. Dzyuba,²⁹ S. Easo,^{48,37} U. Egede,⁵² V. Egorychev,³⁰ S. Eidelman,³³ D. van Eijk,⁴⁰ S. Eisenhardt,⁴⁹ U. Eitschberger,⁹ R. Ekelhof,⁹ L. Eklund,^{50,37} I. El Rifai,⁵ Ch. Elsasser,³⁹ D. Elsby,⁴⁴ A. Falabella,^{14,e} C. Färber,¹¹ G. Fardell,⁴⁹ C. Farinelli,⁴⁰ S. Farry,⁵¹ V. Fave,³⁸ D. Ferguson,⁴⁹ V. Fernandez Albor,³⁶ F. Ferreira Rodrigues,¹ M. Ferro-Luzzi,³⁷ S. Filippov,³² M. Fiore,¹⁶ C. Fitzpatrick,³⁷ M. Fontana,¹⁰ F. Fontanelli,^{19,i} R. Forty,³⁷ O. Francisco,² M. Frank,³⁷ C. Frei,³⁷ M. Frosini,^{17,f} S. Furcas,²⁰ E. Furfaro,^{23,k} A. Gallas Torreira,³⁶ D. Galli,^{14,c} M. Gandelman,² P. Gandini,⁵⁸ Y. Gao,³ J. Garofoli,⁵⁸ P. Garosi,⁵³ J. Garra Tico,⁴⁶ L. Garrido,³⁵ C. Gaspar,³⁷ R. Gauld,⁵⁴ E. Gersabeck,¹¹ M. Gersabeck,⁵³ T. Gershon,^{47,37} Ph. Ghez,⁴ V. Gibson,⁴⁶ L. Giubega,²⁸ V. V. Gligorov,³⁷ C. Göbel,⁵⁹ D. Golubkov,³⁰ A. Golutvin,^{52,30,37} A. Gomes,² H. Gordon,⁵⁴ M. Grabalosa Gándara,⁵ R. Graciani Diaz,³⁵ L. A. Granado Cardoso,³⁷ E. Graugés,³⁵ G. Graziani,¹⁷ A. Grecu,²⁸ E. Greening,⁵⁴ S. Gregson,⁴⁶ P. Griffith,⁴⁴ O. Grünberg,⁶⁰ B. Gui,⁵⁸ E. Gushchin,³² Yu. Guz,^{34,37} T. Gys,³⁷ C. Hadjivasiliou,⁵⁸ G. Haefeli,³⁸ C. Haen,³⁷ S. C. Haines,⁴⁶ S. Hall,⁵² B. Hamilton,⁵⁷ T. Hampson,⁴⁵

- S. Hansmann-Menzemer,¹¹ N. Harnew,⁵⁴ S. T. Harnew,⁴⁵ J. Harrison,⁵³ T. Hartmann,⁶⁰ J. He,³⁷ T. Head,³⁷ V. Heijne,⁴⁰ K. Hennessy,⁵¹ P. Henrard,⁵ J. A. Hernando Morata,³⁶ E. van Herwijnen,³⁷ A. Hicheur,¹ E. Hicks,⁵¹ D. Hill,⁵⁴ M. Hoballah,⁵ M. Holtrop,⁴⁰ C. Hombach,⁵³ P. Hopchev,⁴ W. Hulsbergen,⁴⁰ P. Hunt,⁵⁴ T. Huse,⁵¹ N. Hussain,⁵⁴ D. Hutchcroft,⁵¹ D. Hynds,⁵⁰ V. Iakovenko,⁴³ M. Idzik,²⁶ P. Ilten,¹² R. Jacobsson,³⁷ A. Jaeger,¹¹ E. Jans,⁴⁰ P. Jaton,³⁸ A. Jawahery,⁵⁷ F. Jing,³ M. John,⁵⁴ D. Johnson,⁵⁴ C. R. Jones,⁴⁶ C. Joram,³⁷ B. Jost,³⁷ M. Kaballo,⁹ S. Kandybei,⁴² W. Kanso,⁶ M. Karacson,³⁷ T. M. Karbach,³⁷ I. R. Kenyon,⁴⁴ T. Ketel,⁴¹ A. Keune,³⁸ B. Khanji,²⁰ O. Kochebina,⁷ I. Komarov,³⁸ R. F. Koopman,⁴¹ P. Koppenburg,⁴⁰ M. Korolev,³¹ A. Kozlinskiy,⁴⁰ L. Kravchuk,³² K. Kreplin,¹¹ M. Kreps,⁴⁷ G. Krocker,¹¹ P. Krokovny,³³ F. Kruse,⁹ M. Kucharczyk,^{20,25,j} V. Kudryavtsev,³³ T. Kvaratskheliya,^{30,37} V. N. La Thi,³⁸ D. Lacarrere,³⁷ G. Lafferty,⁵³ A. Lai,¹⁵ D. Lambert,⁴⁹ R. W. Lambert,⁴¹ E. Lanciotti,³⁷ G. Lanfranchi,¹⁸ C. Langenbruch,³⁷ T. Latham,⁴⁷ C. Lazzeroni,⁴⁴ R. Le Gac,⁶ J. van Leerdam,⁴⁰ J.-P. Lees,⁴ R. Lefèvre,⁵ A. Leflat,³¹ J. Lefrançois,⁷ S. Leo,²² O. Leroy,⁶ T. Lesiak,²⁵ B. Leverington,¹¹ Y. Li,³ L. Li Gioi,⁵ M. Liles,⁵¹ R. Lindner,³⁷ C. Linn,¹¹ B. Liu,³ G. Liu,³⁷ S. Lohn,³⁷ I. Longstaff,⁵⁰ J. H. Lopes,² N. Lopez-March,³⁸ H. Lu,³ D. Lucchesi,^{21,q} J. Luisier,³⁸ H. Luo,⁴⁹ F. Machefert,⁷ I. V. Machikhiliyan,^{4,30} F. Maciuc,²⁸ O. Maev,^{29,37} S. Malde,⁵⁴ G. Manca,^{15,d} G. Mancinelli,⁶ U. Marconi,¹⁴ R. Märki,³⁸ J. Marks,¹¹ G. Martellotti,²⁴ A. Martens,⁸ A. Martín Sánchez,⁷ M. Martinelli,⁴⁰ D. Martinez Santos,⁴¹ D. Martins Tostes,² A. Massafferri,¹ R. Matev,³⁷ Z. Mathe,³⁷ C. Matteuzzi,²⁰ E. Maurice,⁶ A. Mazurov,^{16,32,37,e} B. Mc Skelly,⁵¹ J. McCarthy,⁴⁴ A. McNab,⁵³ R. McNulty,¹² B. Meadows,^{56,54} F. Meier,⁹ M. Meissner,¹¹ M. Merk,⁴⁰ D. A. Milanese,⁸ M.-N. Minard,⁴ J. Molina Rodriguez,⁵⁹ S. Monteil,⁵ D. Moran,⁵³ P. Morawski,²⁵ A. Mordà,⁶ M. J. Morello,^{22,s} R. Mountain,⁵⁸ I. Mous,⁴⁰ F. Muheim,⁴⁹ K. Müller,³⁹ R. Muresan,²⁸ B. Muryn,²⁶ B. Muster,³⁸ P. Naik,⁴⁵ T. Nakada,³⁸ R. Nandakumar,⁴⁸ I. Nasteva,¹ M. Needham,⁴⁹ S. Neubert,³⁷ N. Neufeld,³⁷ A. D. Nguyen,³⁸ T. D. Nguyen,³⁸ C. Nguyen-Mau,^{38,o} M. Nicol,⁷ V. Niess,⁵ R. Niet,⁹ N. Nikitin,³¹ T. Nikodem,¹¹ A. Nomerotski,⁵⁴ A. Novoselov,³⁴ A. Oblakowska-Mucha,²⁶ V. Obraztsov,³⁴ S. Oggero,⁴⁰ S. Ogilvy,⁵⁰ O. Okhrimenko,⁴³ R. Oldeman,^{15,d} M. Orlandea,²⁸ J. M. Otalora Goicochea,² P. Owen,⁵² A. Oyanguren,³⁵ B. K. Pal,⁵⁸ A. Palano,^{13,b} M. Palutan,¹⁸ J. Panman,³⁷ A. Papanestis,⁴⁸ M. Pappagallo,⁵⁰ C. Parkes,⁵³ C. J. Parkinson,⁵² G. Passaleva,¹⁷ G. D. Patel,⁵¹ M. Patel,⁵² G. N. Patrick,⁴⁸ C. Patrignani,^{19,i} C. Pavel-Nicorescu,²⁸ A. Pazos Alvarez,³⁶ A. Pellegrino,⁴⁰ G. Penso,^{24,l} M. Pepe Altarelli,³⁷ S. Perazzini,^{14,c} E. Perez Trigo,³⁶ A. Pérez-Calero Yzquierdo,³⁵ P. Perret,⁵ M. Perrin-Terrin,⁶ G. Pessina,²⁰ K. Petridis,⁵² A. Petrolini,^{19,i} A. Phan,⁵⁸ E. Picatoste Olloqui,³⁵ B. Pietrzyk,⁴ T. Pilař,⁴⁷ D. Pinci,²⁴ S. Playfer,⁴⁹ M. Plo Casasus,³⁶ F. Polci,⁸ G. Polok,²⁵ A. Poluektov,^{47,33} E. Polcarpo,² A. Popov,³⁴ D. Popov,¹⁰ B. Popovici,²⁸ C. Potterat,³⁵ A. Powell,⁵⁴ J. Prisciandaro,³⁸ A. Pritchard,⁵¹ C. Prouve,⁷ V. Pugatch,⁴³ A. Puig Navarro,³⁸ G. Punzi,^{22,r} W. Qian,⁴ J. H. Rademacker,⁴⁵ B. Rakotomiamanana,³⁸ M. S. Rangel,² I. Raniuk,⁴² N. Rauschmayr,³⁷ G. Raven,⁴¹ S. Redford,⁵⁴ M. M. Reid,⁴⁷ A. C. dos Reis,¹ S. Ricciardi,⁴⁸ A. Richards,⁵² K. Rinnert,⁵¹ V. Rives Molina,³⁵ D. A. Roa Romero,⁵ P. Robbe,⁷ D. A. Roberts,⁵⁷ E. Rodrigues,⁵³ P. Rodriguez Perez,³⁶ S. Roiser,³⁷ V. Romanovsky,³⁴ A. Romero Vidal,³⁶ J. Rouvinet,³⁸ T. Ruf,³⁷ F. Ruffini,²² H. Ruiz,³⁵ P. Ruiz Valls,³⁵ G. Sabatino,^{24,k} J. J. Saborido Silva,³⁶ N. Sagidova,²⁹ P. Sail,⁵⁰ B. Saitta,^{15,d} V. Salustino Guimaraes,² C. Salzmann,³⁹ B. Sanmartin Sedes,³⁶ M. Sannino,^{19,i} R. Santacesaria,²⁴ C. Santamarina Rios,³⁶ E. Santovetti,^{23,k} M. Sapunov,⁶ A. Sarti,^{18,l} C. Satriano,^{24,m} A. Satta,²³ M. Savrie,^{16,e} D. Savrina,^{30,31} P. Schaack,⁵² M. Schiller,⁴¹ H. Schindler,³⁷ M. Schlupp,⁹ M. Schmelling,¹⁰ B. Schmidt,³⁷ O. Schneider,³⁸ A. Schopper,³⁷ M.-H. Schune,⁷ R. Schwemmer,³⁷ B. Sciascia,¹⁸ A. Sciubba,²⁴ M. Seco,³⁶ A. Semennikov,³⁰ I. Sepp,⁵² N. Serra,³⁹ J. Serrano,⁶ P. Seyfert,¹¹ M. Shapkin,³⁴ I. Shapoval,^{16,42} P. Shatalov,³⁰ Y. Shcheglov,²⁹ T. Shears,^{51,37} L. Shekhtman,³³ O. Shevchenko,⁴² V. Shevchenko,³⁰ A. Shires,⁵² R. Silva Coutinho,⁴⁷ M. Sirendi,⁴⁶ T. Skwarnicki,⁵⁸ N. A. Smith,⁵¹ E. Smith,^{54,48} J. Smith,⁴⁶ M. Smith,⁵³ M. D. Sokoloff,⁵⁶ F. J. P. Soler,⁵⁰ F. Soomro,¹⁸ D. Souza,⁴⁵ B. Souza De Paula,² B. Spaan,⁹ A. Sparkes,⁴⁹ P. Spradlin,⁵⁰ F. Stagni,³⁷ S. Stahl,¹¹ O. Steinkamp,³⁹ S. Stoica,²⁸ S. Stone,⁵⁸ B. Storaci,³⁹ M. Straticiu,²⁸ U. Straumann,³⁹ V. K. Subbiah,³⁷ L. Sun,⁵⁶ S. Swientek,⁹ V. Syropoulos,⁴¹ M. Szczekowski,²⁷ P. Szczypka,^{38,37} T. Szumlak,²⁶ S. T'Jampens,⁴ M. Teklishyn,⁷ E. Teodorescu,²⁸ F. Teubert,³⁷ C. Thomas,⁵⁴ E. Thomas,³⁷ J. van Tilburg,¹¹ V. Tisserand,⁴ M. Tobin,³⁸ S. Tolk,⁴¹ D. Tonelli,³⁷ S. Topp-Joergensen,⁵⁴ N. Torr,⁵⁴ E. Tournefier,^{4,52} S. Tourneur,³⁸ M. T. Tran,³⁸ M. Tresch,³⁹ A. Tsaregorodtsev,⁶ P. Tsopelas,⁴⁰ N. Tuning,⁴⁰ M. Ubeda Garcia,³⁷ A. Ukleja,²⁷ D. Urner,⁵³ A. Ustyuzhanin,^{52,p} U. Uwer,¹¹ V. Vagnoni,¹⁴ G. Valenti,¹⁴ A. Vallier,⁷ M. Van Dijk,⁴⁵ R. Vazquez Gomez,¹⁸ P. Vazquez Regueiro,³⁶ C. Vázquez Sierra,³⁶ S. Vecchi,¹⁶ J. J. Velthuis,⁴⁵ M. Veltri,^{17,g} G. Veneziano,³⁸ M. Vesterinen,³⁷ B. Viaud,⁷ D. Vieira,² X. Vilasis-Cardona,^{35,n} A. Vollhardt,³⁹ D. Volyanskyy,¹⁰ D. Voong,⁴⁵ A. Vorobyev,²⁹ V. Vorobyev,³³ C. Voß,⁶⁰ H. Voss,¹⁰ R. Waldi,⁶⁰ C. Wallace,⁴⁷ R. Wallace,¹² S. Wandernoth,¹¹ J. Wang,⁵⁸ D. R. Ward,⁴⁶

N. K. Watson,⁴⁴ A. D. Webber,⁵³ D. Websdale,⁵² M. Whitehead,⁴⁷ J. Wicht,³⁷ J. Wiechczynski,²⁵ D. Wiedner,¹¹ L. Wiggers,⁴⁰ G. Wilkinson,⁵⁴ M. P. Williams,^{47,48} M. Williams,⁵⁵ F. F. Wilson,⁴⁸ J. Wimberley,⁵⁷ J. Wishahi,⁹ M. Witek,²⁵ S. A. Wotton,⁴⁶ S. Wright,⁴⁶ S. Wu,³ K. Wyllie,³⁷ Y. Xie,^{49,37} Z. Xing,⁵⁸ Z. Yang,³ R. Young,⁴⁹ X. Yuan,³ O. Yushchenko,³⁴ M. Zangoli,¹⁴ M. Zavertyaev,^{10,a} F. Zhang,³ L. Zhang,⁵⁸ W. C. Zhang,¹² Y. Zhang,³ A. Zhelezov,¹¹ A. Zhokhov,³⁰ L. Zhong,³ and A. Zvyagin³⁷

(LHCb Collaboration)

- ¹Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
²Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
³Center for High Energy Physics, Tsinghua University, Beijing, China
⁴LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France
⁵Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
⁶CPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
⁷LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
⁸LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
⁹Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
¹⁰Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
¹¹Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
¹²School of Physics, University College Dublin, Dublin, Ireland
¹³Sezione INFN di Bari, Bari, Italy
¹⁴Sezione INFN di Bologna, Bologna, Italy
¹⁵Sezione INFN di Cagliari, Cagliari, Italy
¹⁶Sezione INFN di Ferrara, Ferrara, Italy
¹⁷Sezione INFN di Firenze, Firenze, Italy
¹⁸Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy
¹⁹Sezione INFN di Genova, Genova, Italy
²⁰Sezione INFN di Milano Bicocca, Milano, Italy
²¹Sezione INFN di Padova, Padova, Italy
²²Sezione INFN di Pisa, Pisa, Italy
²³Sezione INFN di Roma Tor Vergata, Roma, Italy
²⁴Sezione INFN di Roma La Sapienza, Roma, Italy
²⁵Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
²⁶Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Kraków, Poland
²⁷National Center for Nuclear Research (NCBJ), Warsaw, Poland
²⁸Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
²⁹Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
³⁰Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
³¹Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
³²Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
³³Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
³⁴Institute for High Energy Physics (IHEP), Protvino, Russia
³⁵Universitat de Barcelona, Barcelona, Spain
³⁶Universidad de Santiago de Compostela, Santiago de Compostela, Spain
³⁷European Organization for Nuclear Research (CERN), Geneva, Switzerland
³⁸Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
³⁹Physik-Institut, Universität Zürich, Zürich, Switzerland
⁴⁰Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
⁴¹Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
⁴²NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
⁴³Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
⁴⁴University of Birmingham, Birmingham, United Kingdom
⁴⁵H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
⁴⁶Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
⁴⁷Department of Physics, University of Warwick, Coventry, United Kingdom
⁴⁸STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
⁴⁹School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
⁵⁰School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
⁵¹Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

⁵²*Imperial College London, London, United Kingdom*⁵³*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*⁵⁴*Department of Physics, University of Oxford, Oxford, United Kingdom*⁵⁵*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*⁵⁶*University of Cincinnati, Cincinnati, Ohio, USA*⁵⁷*University of Maryland, College Park, Maryland, USA*⁵⁸*Syracuse University, Syracuse, New York, USA*⁵⁹*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil,**(associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)*⁶⁰*Institut für Physik, Universität Rostock, Rostock, Germany,**(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*^aAlso at Università di Bari, Bari, Italy.^bAlso at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.^cAlso at Università di Bologna, Bologna, Italy.^dAlso at Università di Cagliari, Cagliari, Italy.^eAlso at Università di Ferrara, Ferrara, Italy.^fAlso at Università di Firenze, Firenze, Italy.^gAlso at Università di Urbino, Urbino, Italy.^hAlso at Università di Modena e Reggio Emilia, Modena, Italy.ⁱAlso at Università di Genova, Genova, Italy.^jAlso at Università di Milano Bicocca, Milano, Italy.^kAlso at Università di Roma Tor Vergata, Roma, Italy.^lAlso at Università di Roma La Sapienza, Roma, Italy.^mAlso at Università della Basilicata, Potenza, Italy.ⁿAlso at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.^oAlso at Hanoi University of Science, Hanoi, Viet Nam.^pAlso at Institute of Physics and Technology, Moscow, Russia.^qAlso at Università di Padova, Padova, Italy.^rAlso at Università di Pisa, Pisa, Italy.^sAlso at Scuola Normale Superiore, Pisa, Italy.